Effects of Temperature and Sludge Ratio on Anaerobic Co-Digestion of Food Waste and Sewage Sludge

著者	TAO ZHANG
学位授与機関	Tohoku University
学位授与番号	11301甲第19292号
URL	http://hdl.handle.net/10097/00130570

ちょう　とう
氏　　　　　　名　張　　涛
研究科，専攻の名称　東北大学大学院工学研究科（博士課程）土木工学専攻
学 位 論 文 題 目　食品廃棄物と下水汚泥の混合消化に及ぼす温度と汚泥比率の影響
論 文 審 査 委 員　主査　東北大学教授　李　玉友　　東北大学教授　西村　修
東北大学準教授　久保田　健吾

論文内容要約

This dissertation was concerned about the current issues of food waste and sewage sludge treatment, since the two typic wastes take the big proportion of solid wastes in modern society. A sustainable treatment option is required for the stabilizati of food waste and sewage sludge. On the other hand, it has been widely accepted that huge amount of fossil fuel consumpti has become un-sustainable, and numerous renewable energy sources have been explored, in which anaerobic digestion is one the most promising technologies. Organic waste reduction and renewable energy production could be achieved at the same ti in anaerobic digestion, after adequate post-treatment the digestate could also reused as fertilizer and soil amendment. Nonethel there are numerous problems with the stabilization of food waste and sewage sludge by means of anaerobic digestion to dispo food waste and sewage sludge as mono-substrate. For the AD process of food waste, problems such as foaming, volatile fa acids accumulation, lack of nutrient elements, have limited the potential application of anaerobic digestion furtherly. As far sewage sludge digestion is concerned, slit, sand, gravel, and other inertial matter might be present in the sludge, which makes the digestion more difficult and low biogas yield, resulting in a high operation cost and low destruction efficiency. The corresponding bottlenecks could probably be solved by the concept of anaerobic co-digestion. At first, multi substrates stabilization simultaneously could unify management methodologies and share treatment facilities to make use of all shared equipment more efficiently. On the other hand, supply of trace elements, re-balance of nutrients, dilution of heavy metals could also be achieved by co-digestion. Mixing ratios and operation temperature would play key roles in the performance and stability of co-digestion. However, there is a void in the current knowledge that how the mixing ratios impact on the performance and stability under thermophilic and mesophilic co-digestion of food waste and sewage sludge, respectively. Thus this present study was methodically conducted to reveal the co-digestion system's evolution of different mixing ratios under thermophilic and mesophilic conditions.

The first study in this dissertation, as shown in Chapter 3, investigated the thermophilic co-digestion system's dynamics when sewage sludge was added by 0% (RUN1), 25% (RUN2) and 50% (RUN3), respectively. From RUN1 to RUN2, biogas production decreased from 2.73 to 2.51 L/L/d and VS reduction efficiency decreased from 84.2 to 78.6%. VFA concentration was held within low levels and TAN was below 2100 mg/L, indicating a stable operation could be obtained. However, with further addition of sewage sludge in RUN3, total ammonia nitrogen concentration significantly increased to 3263 mg/L in former period, with relatively high level of VFA. The peak value reached as high as 4639 mg/L and severe accumulation of VFA and rapid decrement of pH was observed, the former sharply increased to more than 21,000 mg-HAc/L and the latter decreased from 8.0 to 7.1 rapidly. The biogas production quickly decreased to 0.61 L/L/d, and the methane content also dropped from 59% to 37%. It was suggested that the methane fermentation process was strongly inhibited by high level of TAN. After calculation of ionized and free ammonia, we found that the peak value of free ammonia amounted to more than 1500 mg/L. Higher temperature and pH tends to raise up the percentage of FAN among TAN. As free ammonia is of higher poisonous effect, excess free ammonia concentration was supposed to be the reason of inhibition. Supply of minerals was the synergistic effect of co-digestion. Iron, cobalt and nickel were supplied in RUN1 while no external minerals were supplied in RUN2. At first, the microbial yield coefficient was worked out based on nitrogen element balance and then it was utilized to infer the theoretic required amount of microbial reproduction. After comparison of theoretic and experimental amount of iron, cobalt and nickel, we found that experimental amount brought by addition of sewage sludge was enough to cover up the theoretic requirements based on the microbial yield. In this present study, it could be concluded that for the high solids co-digestion of food waste and sewage sludge, the optimum ratio of sewage sludge was 25%, at which the synergistic effect enhanced the stability while inhibition of high TAN concentration could be avoided.

The second study in this dissertation, as shown in Chapter 4, also surveyed and compared the impact of different sewage sludge ratios from 0, 25,50 and 100%. Biogas yield decreased nearly to a linear way from 0.82 to 0.59 L/g-VS_{in}. The organic destruction efficiency also contended a similar way. It could be concluded that the degradation process of such two kinds of substrates was independent from each other. However, the protein removal efficiency remained within quite low levels across four RUNs. When sewage sludge ratio increased gradually from RUN1 to RUN4, the TAN level also increased in a linear way, indicating that TAN level was closely related to sewage sludge ratio. The peak value of TAN appeared in RUN4, which was 3800 mg/L. In spite of relatively high TAN level in RUN4, there was no sign of inhibition. During the whole operation period, it was held stably with low VFA concentration, which was no more than 100 mg-HAc/L. The total alkalinity in across 4 RUNs was maintained between 5652 and 9943 mg-$CaCO_3$/L. pH varied from 7.38 to 7.57. High buffering capacity, adequate pH and low VFA level, made the fermentation process into a stable condition. On the other hand, we calculated whether addition of sewage sludge could cover up the required amount of microbial reproduction. At first, methane production stoichiometry was developed through nitrogen element balance, which was shown as below:

$$C_5H_{8.58}O_{3.05}N_{0.29}+0.89H_2O \rightarrow 0.17C_5H_7O_2N + 2.29CH_4 + 1.76CO_2 + 0.13NH_4HCO_3 \quad RUN1$$

$$C_5H_{8.66}O_{3.16}N_{0.35}+0.87H_2O \rightarrow 0.16C_5H_7O_2N + 2.26CH_4 + 1.75CO_2 + 0.19NH_4HCO_3 \quad RUN2$$

$$C_5H_{8.76}O_{3.30}N_{0.39}+0.87H_2O \rightarrow 0.15C_5H_7O_2N + 2.26CH_4 + 1.76CO_2 + 0.25NH_4HCO_3 \quad RUN3$$

$$C_5H_{9.00}O_{3.64}N_{0.57}+1.02H_2O \rightarrow 0.08C_5H_7O_2N + 2.29CH_4 + 1.80CO_2 + 0.49NH_4HCO_3 \quad RUN4$$

Throughout the stoichiometry, co-digestion of food waste and sewage sludge could be well predicted. Seen from the 4 stoichiometry, methane yield decreased and produced ammonia increased along with increasing sewage sludge mixing ratios. It was noteworthy that the microbial yield coefficient was positively correlated to C/N ratio of substrates, which could be utilized as references to supply minerals. And then microbial yield coefficient was calculated for each RUN and then theoretic required amount of microbial reproduction for iron, cobalt and nickel was inferred to be 40-230, 0.56-9.63 and 3.34-16.06 mg/kg-$COD_{removed}$. The analysis of soluble elements by ICP-MS showed that sewage sludge was able to supply enough mineral elements for microorganism reproduction. We also carried out energy assessment of co-digestion concerning about 4 mixing ratios. The net energy production across the 4 RUNs was 14.81, 14.21, 12.52 and 10.80, respectively. The decreasing trend provided a proof to decide the mixing ratios from the perspective of energy production. At last, the stable operation across the whole process implied that sewage sludge could be added at any mixing ratios according to the practical collecting amount of food waste and sewage sludge.

The third study in this dissertation, as shown in Chapter 5, compared the difference between thermophilic and mesophilic co-digestion of food waste and sewage sludge. At first, biogas production and organic removal efficiency both decreased with higher mixing ratios of sewage sludge in thermophilic and mesophilic co-digestion. For the mono-digestion of food waste and 25% addition, thermophilic reactors could be operated with higher removal efficiency and biogas yield. However, more ammonia nitrogen was released with higher removal efficiency. Thus throughout the experiment, it was observed that thermophilic co-digestion had higher TAN level than the mesophilic. In the case of 50% addition of sewage sludge, TAN concentration for the thermophilic and mesophilic was 3263 and 2284 mg/L on average. Much higher pH and alkalinity in thermophilic reactor was also observed. According to the ionized and free ammonia nitrogen (FAN) distribution formula, FAN proportion would increase with higher pH and temperature. During the inhibition period, FAN in thermophilic reactor was as high as 28.3% (1500 mg/L) while the peak value of FAN in mesophilic reactor was only 3.5% (122 mg/L) for the mono-digestion of sewage sludge. As a matter of high toxicity, FAN inhibited the methanogenesis activity, the product of acidogenesis phase was then accumulated, leading to the decrement of biogas production. The VFA concentration reached 21,000 mg-HAc/L. The relationship between TAN level and VFA concentration was simulated by a modified Gompertz model, showing that the initial inhibition threshold was 2168 mg/L. This could provide a reference for the control of TAN concentration in thermophilic co-digestion. More attention should be paid to nitrogen content in high-solids methane fermentation, especially for the readily biodegradable substrates. For the mesophilic condition, when mixing ratio was 50% and 100%, methane fermentation could be operated stably. Thermophilic co-digestion has higher efficiency when mixing ratio of sewage sludge was low, while mesophilic condition could be operated with much wider range of variation of mixing ratios.

Chapter 6 concluded the results of this present study and illustrated the perspective of application in the future.

As described above, this study clarified the characteristics of methane and sewage sludge in mono-digestion and co-digerstion through long-term continuous experiments and data analysis. The microbial yield coefficient under each fermentation condition was evaluated, and ammonia inhibition and nutrient supply were analyzed. The results of this research will provide basic knowledge for the process design and operation of high-solid methane fermentation of municipal waste, and contribute to renewable energy production and recycling-oriented society construction, and promote the development of environmental engineering.